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# Highly carbide filled composite materials for the mining and drilling industry

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The mining and drilling industry has a need for highly wear resistant large diameter drill heads. The manufacturing of such drill heads takes place by near net shape infiltration of a powder matrix using tungsten carbides with copper based infiltration alloys. The drill heads are exposed to different geologic formations which triggers a desire for very flexible design parameters resulting in a complex need for both high wear resistance, but also high bending strength as well as good repair-ability. Such contradictory needs have to be solved using adjusted carbide compositions. The paper covers an area where only little information has been published so far. It is written from an Industry point of view and presents the industrial production routine for the drill heads as well as the current state of the art material solutions. The influences of different types of carbides, particle sizes and compositions on the resulting properties will be discussed. Additionally, the paper will show recent challenges of the drilling industry resulting from the shale gas boom.

## 1 Technical challenges for drill heads used in oil and gas exploration

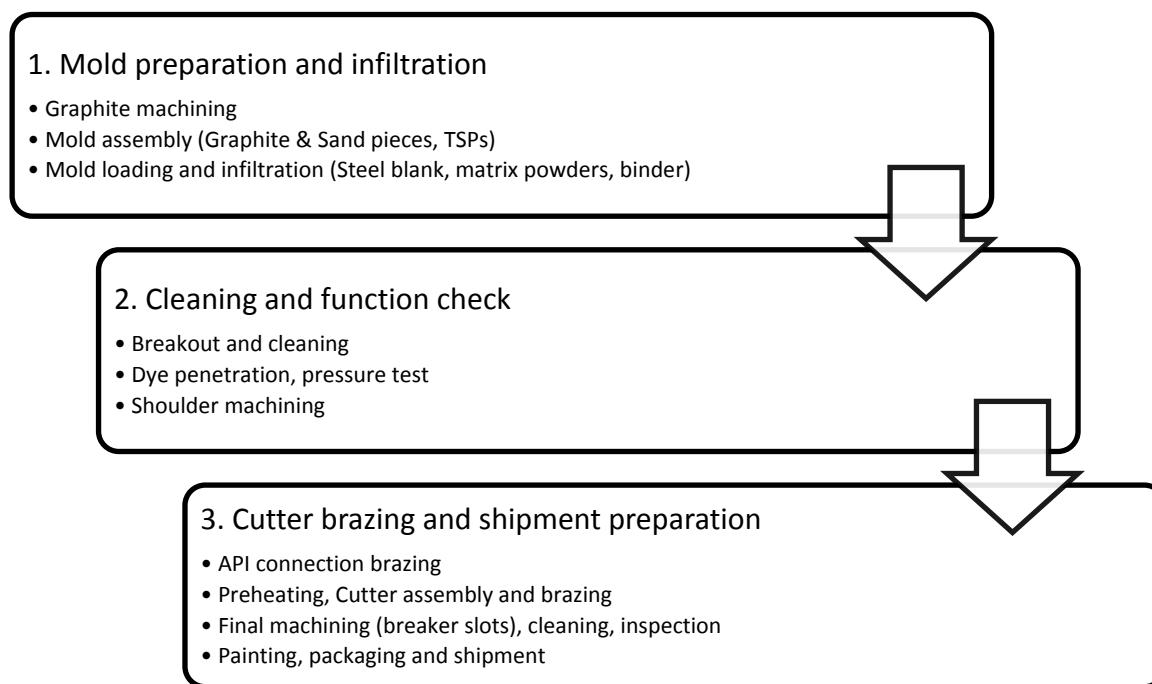
The drilling service industry offers a large variety of drill heads in order to optimize the drilling performance in the field. Roller Cones and Matrix bits as well as Steel Body bits equipped with PDCs (Poly Crystalline Diamond Cutters) are the most important examples. The drilling performance is often expressed as Rate of Penetration (ROP), which is a term for the drilled distance per time unit and strongly depends on the selection of the drill head as well as the drilling parameters, e.g. the rotation speed. Optimizing the ROP usually results out of the right balance between drilling speed and durability of the drill head. Therefore, different drill head designs have been developed. For PDC bits, the number and height of the blades are the most important design factors next to the number, angle and location of the diamond cutters. Such geometrical designs require the adjustment and optimization of material related properties such as TRS (Transverse Rupture Strength, ASTM B406) and abrasion/erosion resistance (e.g. according to ASTM B611, ASTM G65, ASTM G75) in order to avoid early failures in the field. Generally speaking, the advantage of matrix body bits is the outstanding wear resistance whereas steel body bits have a lower wear resistance requiring an additional coating but superior TRS. The focus of this paper is the material design of matrix body bits representing a highly heterogeneous composite material based on a metallic binder and carbide hard phases. Therefore, the measurement and in depth understanding of the related mechanical properties of such composite materials is a major precondition for the development of optimized drill head compositions.

## 2 Industrial drill head manufacturing process

The industrial manufacturing of matrix PDS drill heads can be divided into three major process steps as shown in figure 1. In the first step the desired geometry of the drill head is machined as a negative form out of a graphite block. Subsequently the carbide powders will be poured out into the graphite mold and infiltrated with a binder to form the solid bit body. The infiltration binder is a Cu/Mn/Ni/Zn alloy with a melting point above 900 °C. The target of step one is to produce a crack-free solid carbide body. This will be tested in step two using dye penetration of the body and pressure testing of the noz-



zle areas. Step three requires careful preheating of the bit body as well as the cutter pockets to prepare the manual diamond cutter brazing process. This is a critical step with respect to the occurrence of cracks which may result in scrapping of the drill head.



**Figure 1:** Three step manufacturing process for matrix body PDC drill heads

Upon usage of the drill head in the field two typical types of wear may occur. Firstly, the diamond cutters can get lost or wear down. Secondly, the matrix body gets eroded away and loses its original shape. Both wear losses can be repaired several times in repair centers to elongate the drill head life as much as possible. The life time of a drill head usually ends due to severe erosion or cracking in the blades after 2-10 repair cycles. The analysis such failure cases as well as the design requirements translate into the desired material properties for the matrix body powder. The reverse engineering of failure mechanisms as well as the development of new matrix powders is a complex matter bearing a high risk of costly issues in the field. A close cooperation and knowledge exchange of the drill bit manufacturers with powder producers and R&D centers has proven to be a successful concept for this challenge. Although some of the established matrix powders did not change a lot over decades and still represent an industry standard, new powder formulations for special applications are continuously under development in order to save cost and improve the most important KPI for drilling, the ROP. As a rule of thumb, 50-60 m/h is a good figure for the ROP.

### 3 State of the art material solutions

The established state of the art materials for matrix PDC drill head manufacturing are exclusively recruited from the family of tungsten carbides. This includes macrocrystalline WC, sintered WC, cast tungsten carbide (CTC) as well as reclaimed powders, crushed hard metals (WC-Co) and sintered WC-Co granules. The wear resistance and bending strength of the final infiltrated drill head strongly depends on the carbide origin as well as the grain size or particle size distribution respectively. Some basic rules for the selection of the best application fits are summarized in table 1.

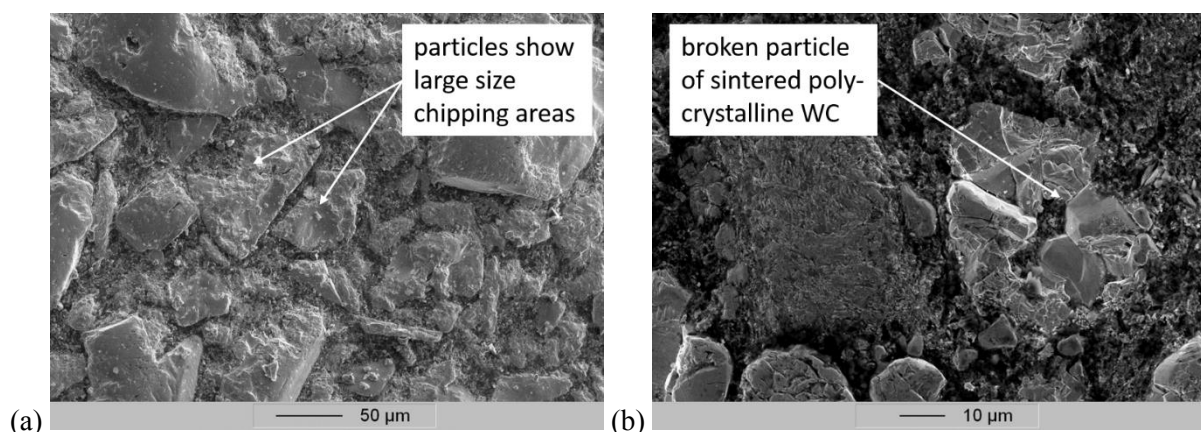
**Table 1:** basic rules for the selection of tungsten carbides for drill head manufacturing

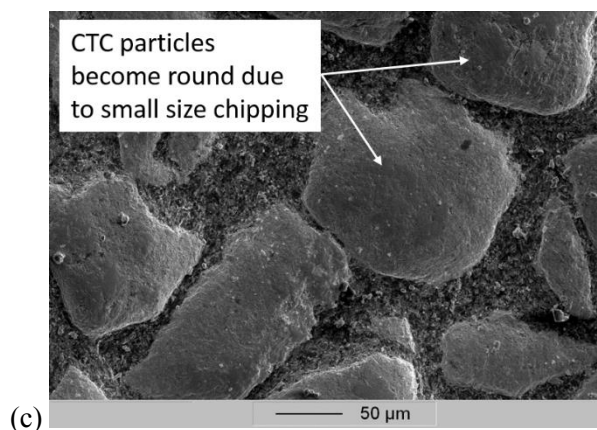
Selection criteria	Variable	Impact on intrinsic carbide properties	Impact on drill head properties
Type of carbide	Sintered, macro-crystalline, crushed, cast	hardness and fracture toughness depend on manufacturing process	Wear resistance increases with higher fracture toughness, e.g. CTC is superior to WC due to the fiber structure. But CTC also dissolves more easily in the binder and forms brittle eta phase.
Grain size and particle size distribution	Roughly 25-1000µm	A wide PSD reduces the porosity of the powder in the mold and therefore the mean free path of the binder	Coarse grains lower abrasion loss but also decrease TRS. A wide PSD improves soft erosion.
Chemistry	Raw material selection, manufacturing process	Impurity level, e.g. O, S, free carbon, trace metals	Usually low TRS because certain impurities disturb the infiltration process resulting in porosity and therefore lower TRS. W2C (e.g. out of CTC) dissolves more easily in the binder and forms brittle eta phase.

Figure 2 documents the visual fracture toughness differences of three types of carbides after G65 (rubber wheel test) wear test treatment. Figure 2 (a) shows a macrocrystalline WC which tends to lose larger chips during the relatively hard erosive G65 test. In figure 2 (b), a polycrystalline WC is shown. In this case the particle had a hollow center and therefore tends to break into larger pieces either. In contrast to this, figure 2 (c) represents a typical CTC matrix powder with high intrinsic fracture toughness. The CTC particles therefore only lose small chips in the G65 test and tend to be more stable, i.e. they usually perform superior in the G65 (also B611) test.

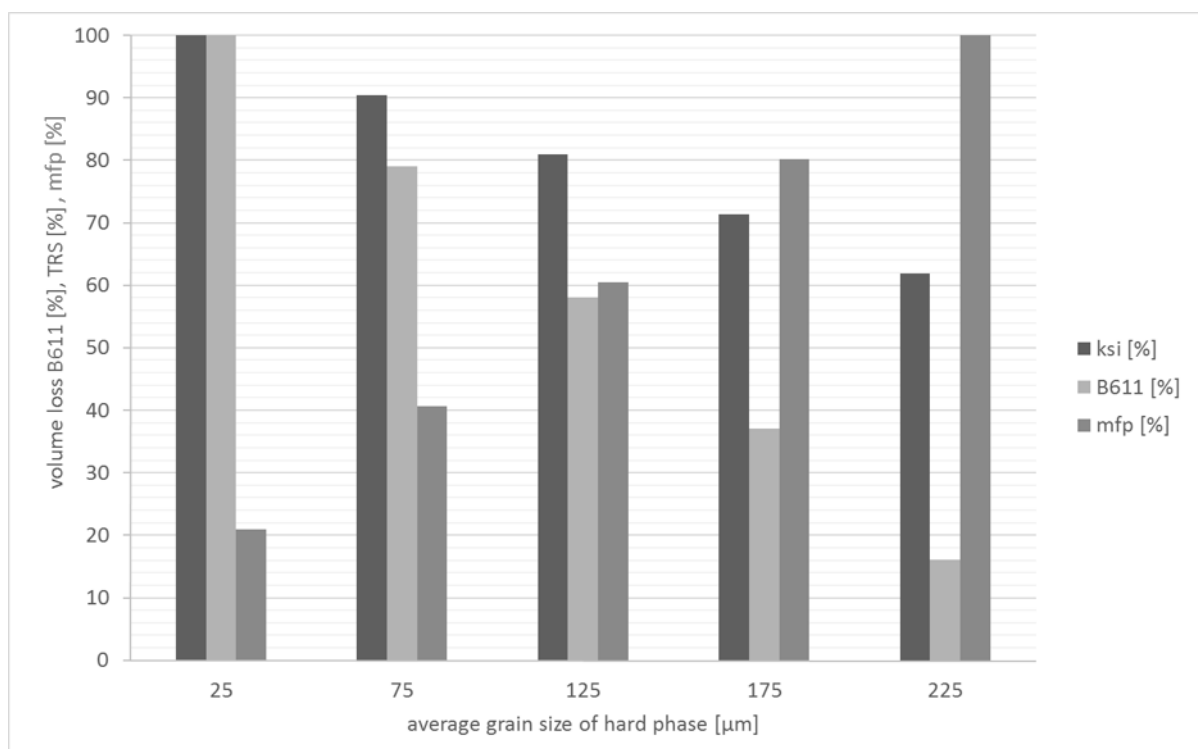
Figure 3 shows the decrease of B611 wear losses but also the decrease of TRS with increasing average grain size of the hard phases (different materials contribute to the average figures). The mean free path (distance between particles which is filled with binder) is by nature larger for coarse particles. However, this does not explain the decrease of TRS.

Figure 4 illustrates the formation of brittle  $\text{Ni}_2\text{W}_4\text{C}$  eta phase in a CTC/binder system.

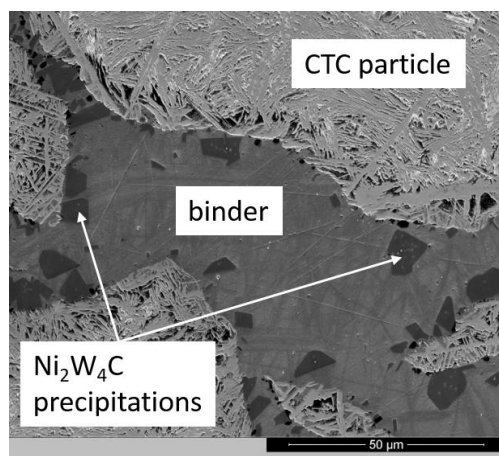




**Figure 2:** (a) Macrocrystalline WC, (b) Sintered WC, (c) CTC, all after G65 treatment



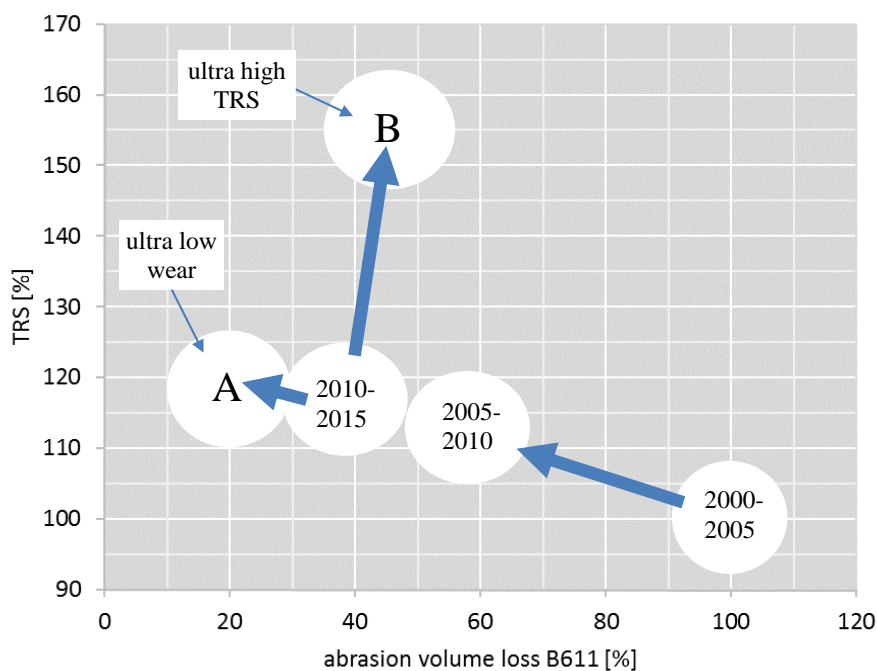
**Figure 3:** Average wear losses according to B611 and average TRS of hard phases with different average grain sizes relative to the figures at 25 $\mu\text{m}$  and mean free path (binder) relative to the figures at 225 $\mu\text{m}$



**Figure 4:** Ni<sub>2</sub>W<sub>4</sub>C eta phase precipitated in the infiltration binder near the CTC particles

The fact that there is still a huge improvement potential for drill head performance but only a few systematic rules are known for material design has led to an increased R&D activity recently.

However, the historic development as shown in figure 5 proves that some key performance figures like the bending strength (TRS) and especially the wear resistance according to ASTM B611 have improved significantly in the recent years (figures relative to year 2000). The current development trends are shown in figure 5 as well. Trend (A) represents the need to continue the historic development of improving the wear resistance without giving up on TRS. Trend (B) reflects a philosophy change into the direction of ultrahigh TRS which has been influenced from the shale gas exploration.



**Figure 5:** Historic development of TRS and B611 wear losses of matrix powders and current development trends A (ultrahigh TRS) and B (ultralow wear)

#### **4 Shale Gas exploration – Conclusions and consequences for the design of new materials**

Shale deposits are known as a “non-conventional” resource for oil and especially natural gas. The exploration of shale gas has become very common in the US in the recent years but in contrast to conventional resources it usually needs both fracking and horizontal drilling of the relatively soft to medium hard formations. This gives priority to the usage of PDC bits, especially those who can be used with a high rotation speed. In relatively soft formations the blades of the drill head should be taller than in hard formations in order to improve the transportation of the crushed stones in the mud. Both, the high rotation speed as well as the tall blades triggers a need for a higher TRS of the matrix body. Therefore, steel body bits are a favorite choice in such environments. The disadvantage of steel body bits is the low wear resistance, which is about 10-20 times lower compared to matrix body bits, e.g. according to soft erosion (G75) testing. Therefore, the development direction (B) as indicated in figure 5 has gained importance recently. In case (B) the matrix bits are supposed to achieve a significant improvement of TRS whereas the wear resistance can be compromised. Materials fulfilling the requirements of trend (B) according to figure 5 are currently under development and/or field testing. Further progress will be reported elsewhere.

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